Anthropocene

Short communication

Humans as the third evolutionary stage of biosphere engineering of rivers

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ABSTRACT

We examine three fundamental changes in river systems induced by innovations of the biosphere, these being: 1) the evolution of oxygenic photosynthesis; 2) the development of vascular plants with root systems; and 3) the evolution of humans. The first two innovations provide context for the degree of human-induced river change. Early river systems of the Precambrian Archean Eon developed in an atmosphere with no free oxygen, and fluvial sediments accumulated 'reduced detrital' minerals such as uraninite, siderite, gersdorffite and pyrite. By 2.4 Ga the evolution of oxygenic photosynthesis produced an oxygenated atmosphere and 'reduced detrital' minerals mostly disappeared from rivers, affording a distinct mineralogical difference from subsequent fluvial deposits. Rivers of the Precambrian and early Phanerozoic were dominantly braided, but from 0.416 Ga, the evolution of vascular plants with roots bound floodplain sediments and fostered fine-grained meandering rivers. Early meandering river deposits show extensive animal activity including fish and arthropod tracks and burrows. *Homo sapiens*, appearing about 150 Ka BP, has, in recent millennia, profoundly modified river systems, altering their mineralogical, morphological and sedimentary state. Changes in sediment fluxes caused by human ‘reverse engineering’ of the terrestrial biosphere include deforestation, irrigation and agriculture. Sediment retention has been encouraged by the construction of dams. Modern river systems are associated with extensive human trace fossils that show a developing complexity from ancient civilizations, through to the gigantic metro systems beneath rivers in modern megacities. Changes induced by humans rank in scale with those caused by earlier biosphere innovations at 2.4 and 0.416 Ga, but would geologically soon revert to a “pre-human” state were humans to become extinct.

Key words: Anthropocene, Earth evolution, biosphere, bioturbation, river engineering

Introduction

Water may have been delivered to the surface of Earth largely by comets and hydrous carbonaceous chondrite meteorites in the Hadean Eon (e.g. Albarède, 2009) after the planet’s accretion at 4.54 Ga (4.54 billion years ago). However, early oceans and rivers were likely vaporized by the continued influx of large asteroids (Kasting and Ono, 2006). After the ‘late heavy bombardment’ of Earth (finishing about 3.9 Ga), water oceans have persisted at the surface, to provide water vapour for rainfall (Fig. 1). From then until the present, rivers have flowed across the evolving landscape of Earth (with the possible exception of the most severe ‘Snowball’ glaciations of the Proterozoic Eon: see Hoffman et al., 1998). Rivers were and remain a key component of the silicate rock weathering cycle and thus a control on the atmospheric level of carbon dioxide (see, for example, Dessert et al., 2003), and they also provide a source of nutrients from weathered terrestrial minerals to supply the ocean biosphere with biologically important materials (e.g. see Meybeck, 2003). There is an extensive geological record of sedimentary deposits formed from rivers, extending back in time to the Archean Eon of the Precambrian (Fig. 1). Examination of river systems in the geological and archaeological record suggests three major step changes in river evolution produced by innovations of the biosphere, involving the evolution of oxygenic photosynthesis at 2.4 Ga (Blankenship, 2010), the development of a terrestrial biosphere with vascular plants, beginning about 0.416 Ga (Davies and Gibling, 2010, 2013), and the geologically recent evolution of *Homo sapiens* (Fig. 1). In this paper we examine human impacts on global river system change using the context of major global changes of the past.

Rivers in a world with an oxygenated atmosphere

The geological record of fossil rivers extends to the Mesoarchean (3.2 to 2.8 Ga) part of the Precambrian (e.g. Rasmussen and Buick, 1999; see Fig. 1). The dearth of river deposits from yet older rocks may reflect the absence of large continental areas on which extensive rivers could flow; or, it may reflect the very incomplete record of sedimentary deposits from Paleo- and Eoarchean rocks. Earth’s Archean atmosphere likely comprised nitrogen, hydrogen, water vapour, methane, ammonia and carbon dioxide, with traces of other gases, but no free oxygen (Kasting and Ono, 2006). Under this atmosphere rivers flowed but accumulated a different suite of minerals to those that formed in the post-Archean, oxygenated atmosphere. These ‘reduced’ minerals include the uranium ore uraninite, the iron mineral pyrite, and the nickel-arsenic mineral gersdorffite (see Rasmussen and Buick, 1999). These minerals occur as detrital grains within sedimentary deposits of ancient Archean braided river systems from as far afield as Australia (Rasmussen and Buick, 1999), South Africa (e.g. Frimmel, 2005) and North America (Koglin et al., 2010). They are important sources of uranium ore. The minerals were sourced from the weathering of yet more ancient Archean granitic intrusions or the pegmatitic mineralization associated with them (Depiné et al., 2013). After 2.4 Ga, these detrital minerals largely disappear from river deposits, reflecting a fundamental change in Earth’s biosphere caused by the evolution of oxygenic photosynthesis and the accumulation of free oxygen in the atmosphere (Blankenship, 2010). A mineralogical distinction thus exists between the river deposits of the Archean, and those of the later geological record. This distinction is pertinent to Anthropocene changes to fluvial systems, which have likewise accumulated a distinctive suite of human-induced mineral and chemical changes not found in the earlier record of rivers. This includes signatures of novel organic compounds (e.g., see Vane et al., 2011) and novel minerals and rocks. The minerals include metals rare or non-existent in nature such as aluminium fragments (Zalasiewicz et al., 2014a) and ‘mineraloids’ such as plastics, both only present as a distinctive and common component of many river sediments (Morritt et al., 2014; Rech et al., 2014) in significant amounts from the mid-20th century. There are also novel rock types including ceramic, brick and concrete fragments entering the sedimentary system in large and increasing amounts. In small amounts, versions of these have been present for millennia, but in recent decades they show rapid growth in quantity (>95% of the circa half-trillion tons of concrete made to date is post mid-20th century) and novel petrographies (such as the addition of fly ash from power stations as a major filler in concrete). Anthropocene river strata in the future will be as petrographically distinctive as we find Archean fluvial lithotypes to be today.

Rivers in a world with a complex terrestrial biosphere

The signatures of the coeval evolution of the terrestrial plant biosphere and its sedimentological and geomorphological impact on river systems have been summarized by Davies and Gibling (2010, 2013). The preserved sedimentary record suggests that many rivers of the Precambrian and Early Palaeozoic adopted a 'sheet-braided' style formed by rapid channel switching and lateral migration of channels over kilometres of floodplain (Davies and Gibling, 2010). Precambrian meandering rivers have left a rare sedimentary record, with only a few known examples of sand-bed or gravel-bed meanders and no proven examples of meandering rivers bounded by fine-grained floodplain deposits (Long, 2011). Precambrian rivers are characterized by sedimentary lithofacies that can be related to modern gravel and boulder beds forming in ephemeral braided systems and debris flows (Paszkowski and Shone, 1994; Long, 2011). Although a terrestrial biosphere of microbial mats in soils may have existed since the late Archean (Watanabe et al., 2000), this biosphere probably impinged little on the morphology of rivers and was inconsequential in preventing fluvial erosion. From about 0.472 Ga (Middle Ordovician), the terrestrial biosphere evolved non-vascular plants (Wellman et al., 2003) followed by the first vascular plants at 0.436 Ga (early Silurian), and later (at 0.416 Ga, Early Devonian), vascular plants with root systems. As land plants evolved and diversified from small embryophytes in the Ordovician through to arborescent forests in the Devonian, alluvial sedimentary rocks show increasing evidence for production (due to enhanced chemical weathering) and retention (due to baffling and binding) of muddy sediment, the disappearance of architecture indicative of the ‘sheet-like’ braided style of rivers, and, coeval with the oldest evidence for deep rooting, the first heterolithic lateral accretion sets, signifying the expansion of fine-grained meandering rivers (Davies and Gibling, 2010). With the further evolution of arborescent vegetation in the Carboniferous, the first anabranching river deposits are suggested to appear in the rock record; their formation and preservation was promoted by the evolution of more stable vegetated floodplains and new avulsion triggers such as stabilized levees, in-channel riparian vegetation and log jams (Davies and Gibling, 2013). This sedimentary record of a Palaeozoic diversification of river styles is accompanied by new suites of trace fossils; the trackways, burrows, feeding and faecal traces of animals - especially arthropods (e.g. Rolfe, 1985), but also other invertebrates and fish (Fig. 2; see also Wisshak et al., 2004). This trace fossil record illustrates the Palaeozoic establishment of non-marine ecosystems and, in rivers particularly, the success of land plants as ecosystem engineers that created new biogeomorphic alluvial habitats for a range of plant and animal life (Davies and Gibling, 2013). The oldest unequivocal alluvial trace fossil assemblages are dominated by arthropod trackways and appear globally in the rock record in Silurian (circa 0.423 Ga) alluvium (Davies et al., 2006; Hunter and Lomas, 2003; Trewin and McNamara, 1995), followed by fish traces and arthropod and other invertebrate burrows which appear and then diversify from the latest Silurian and Devonian (circa 0.419 Ga) onwards (Allen and Williams, 1981; Marriott et al., 2009; Minter et al., in press). The biogeomorphic effects of land plants and the burrowing of alluvial sediments by animals have largely persisted since their first occurrences in the geological record. A perturbation in these effects has been suggested to occur during widespread reduction and turnover of non-marine flora and fauna during the Permian-Triassic Mass Extinction Event at 0.252 Ga (e.g., Benton and Newell, 2014), but even this can only be suggested to have had a temporary effect on river functioning on a geological timescale. Modifications to rivers by plants and animals occur throughout the Mesozoic and Cenozoic and can be considered to be fundamental characteristics of 'pristine' river systems throughout most of the Phanerozoic, providing context to understanding the increasing influence of humans on river morphology through the past 5000 years.

Rivers in a world with humans

Meybeck (2003) has convincingly argued that rivers have been profoundly influenced by humans through wetland drainage, agriculture, the construction of artificial water bodies, and the development of artificial water storage and flow regulation structures. He considered these changes to be a product of the 'Anthroposphere', the sum of human economic activities (including mining, agriculture, industrialization, forestry, and urbanization), and he regarded the degree of change important enough to discuss the 'Anthropocene era'. In combination with the global regulation of water bodies by humans, Meybeck (*op. cit.*, and references therein) also noted a global-scale chemical and biogeochemical modification of terrestrial water bodies. He traced the origins of the human modification of river systems to the third millennium BC, beginning in major rivers associated with the earliest civilizations of the Euphrates (e.g., see Besançon and Geyer, 1996) and Tigris river systems in Mesopotamia (e.g., see Heyvaert et al., 2012), the Nile in Egypt, the Indus in Pakistan, and the Huang He in China. In medium-sized rivers of Western Europe Meybeck (*op. cit*., fig. 2) traced the introduction of organic contaminants and of metals back into the first and second millennia BC, and he identified similar patterns in South America. Later, in the 20th century, new contaminants, nitrates and pesticides became a significant factor in rivers.

The human influence on rivers is evident from classical civilizations bordering the Mediterranean Sea and has been investigated in detail on the coast adjacent to classical Rome (e.g., Goiran et al., 2010). The ancient port of Ostia, for example, shows a clear anthropogenic signature, with the eventual silting-up of the harbour and its abandonment before the start-up of the successor harbour at Portus (Goiran et al., 2014). Near the mouth of the River Tiber, downstream from Rome, construction of the Claudius and Trajanic Canals (Salomon et al., 2012), and of Portus also, significantly altered the sedimentary motif of the naturally formed sediments where the river enters the Tyrrhenian Sea (Bellotti et al., 2007) (Fig. 3). Here there is a clear signal of anthropogenic influence through the development of brackish water conditions in the Claudius harbour signaled by a changing fauna and flora (Sadori et al., 2010), a mineralogical signal from gypsum, a changed sedimentary motif to one dominated by silts and organic mud, and introduced potsherds, wood fragments and bone that signal human activity (Mazzini et al., 2011, fig. 2).

The sedimentological and geomorphological effects of human settlement on river systems can be profound and are often associated with enforced changes to vegetation within river catchments. In northern Europe, floodplain deforestation has continued since 6000 BP, and some medium to large rivers that presently adopt a meandering planform appear to have formerly possessed an anabranching form when forested (Brown, 2002; Davies and Sambrook Smith, 2006). In Australia, the neighbouring Thurra and Cann river catchments provide direct evidence of this effect: the former has retained a ‘pristine’ natural state, whilst the latter has seen extensive logging, riparian deforestation and removal of woody snags since being settled by European colonizers from 1860 onwards (Brooks et al., 2003). During this interval, the Cann River has seen a 360% increase in channel depth, a 240% increase in channel slope, a 700% increase in channel capacity and a very large increase in the rate of lateral channel migration, with the net effect that it is now more straight and wide than the neighbouring Thurra River and its current state is dramatically out of phase with the geomorphic and sedimentary regime that it had maintained for the previous 27 ka (thousand years). In North America, a similar post-colonial effect is seen in the spike in sedimentation rate in alluvium of the Delaware River valley with agricultural land clearance from circa 1600, but even this was preceded by an earlier anthropogenic increase in sedimentation rate around circa 1100, associated with intensified deforestation and maize cultivation during the Medieval Climate Anomaly–Little Ice Age transition (Stinchcomb et al., 2011). In each of these particular instances, changes in alluvial regime have been mediated through anthropogenically-forced vegetation changes, partly inversely analogous to the Palaeozoic rise in influence of land plants in alluvial systems.

During modern times, the human modification of river systems has been accelerating, as succinctly illustrated in the images of dam construction on the rivers of the USA between 1850 and 2000 (Syvitski and Kettner, 2011), and by dams and irrigation systems developing along the river Nile (Woodward et al., 2007). River modification by humans is also associated with the growth of a new phase of “trace fossils”, the towns, cities and megacities that arise along their banks, and the sewerage treatment plants and canals that are associated with these developments. These structures also include the tunneling that is undertaken beneath rivers. Distinctively, the tunnels extend well beyond the immediate river deposits of alluvium, but nevertheless are part of the urban systems that strongly modify rivers. This reached a monumental scale for the first time in the mid nineteenth century with the construction of the Thames Tunnel under the river in London (Fig. 4). Built between 1825 and 1843, the tunnel is 11 m wide, 6 m high and 396 m long, a feat of human engineering guided by the engineers Thomas Cochrane, Marc Isambard Brunel, and Isambard Kingdom Brunel. The tunnel reflects the increasing complexity of human interaction with rivers through technology in the 19th century. It represents a scale of biosphere burrowing many orders of magnitude larger than the burrows seen in ancient river strata (see Fig. 2). Burrowing under the Thames culminated in the vast trace fossil network of the London (Underground) Metro, which began construction in 1861, and now has several lines passing beneath the river Thames. These structures, a visible example of the complexity of modern human structures around rivers, have been considered as marking a key event in the evolution of the biosphere comparable to changes in animal behaviour witnessed by trace fossils in marine deposits at the Precambrian-Cambrian boundary (see Williams et al., 2014) and later in alluvial sediments during the Siluro-Devonian (Minter et al., in press). Human burrow systems are characteristic of many of the world’s great cities from New York to Tokyo.

Though a recognizable stratigraphy can be formulated for changes to rivers over time based on influences from agriculture, transportation, pollution, mining and mineral input, urbanization and reservoir development (e.g. in the UK, see Lewin, 2013), these human-induced changes to rivers cannot be used to define an

Anthropocene Series boundary in sedimentary deposits. Unlike some other potential geological markers of the Anthropocene (see Zalasiewicz et al., 2014b), changes to rivers have been progressive (and so diachronous between regions), having unfolded over several millennia (even in a single region like the UK, e.g. Macklin et al. 2014), and in part (as in the tunneling phenomena) cross-cut earlier rocks.

Rate or state change in global rivers?

One can argue that progressive human changes to rivers over the past 5000 years represent a gradual but accelerating rate change to fluvial processes, particularly the increased flux of sediments (200 km^3 per year) as a product of deforestation, agriculture, mining and transportation systems, or the increased retention of sediment (170 km^3 per year) through the construction of dams (Syvitski et al., 2005; Syvitski and Kettner, 2011). Contemporary human re-engineering of rivers has no real parallel in Earth history. The nearest counterparts are the dams built across streams by beavers, which are themselves geologically recent ecological innovations, with phylogenetic analysis of woodcutting beavers suggesting that they evolved no earlier than the late Oligocene (circa 24 million years ago) (Rybczynski, 2008). Beaver dams are a significant control on sedimentation in particular alluvial settings (Kramer et al., 2012), but the scale and (especially) the complexity of human constructions is orders of magnitude greater. In effect, entire fluvial systems have been integrated within the technosphere (see Haff, 2014) that simultaneously maintains human existence and drives the global changes that have taken the Earth system into the Anthropocene state. Given the importance of fresh water to human existence, it is not surprising that rivers have been more thoroughly re-engineered by humans than any other geomorphic feature. It is this change that we suggest to be of comparable importance to the fundamental transitions of the fluvial system in Earth history. Nevertheless, many of the changes induced by humans would revert to a pre-human ‘natural state’ were humans to become extinct. Analogues exist in tropical South America, where Pre-Colombian societies were decimated by the arrival of Europeans in the sixteenth century, and where ancient ditches and canals built by extensive civilizations have been obliterated by the subsequent accumulation of river alluvium (e.g., Rostain, 2010). Nonetheless, even in these areas, convex structures such as habitation mounds, or raised fields have persisted, providing a clear indication of human modification along the margin of rivers pre-1500 AD (Rostain, *op. cit.*) that includes a faunal and floral signature (Bush and Silman, 2007 and references therein). Thus, a signal of human interference remains, especially in low-lying areas, and includes a well-defined stratigraphic interval of trace fossils along the banks of rivers, especially in megacities (Williams et al., 2014), or chemical signatures from pollutants (Vane et al., 2011; Delile et al., 2014), or a record of altered sedimentary patterns, as for example in the Tiber River downstream of Rome (Mazzini et al., 2011), the Rhone River (Bravard, 2010) or the Nile (Stanley and Warne, 1993). Rivers would likely rework or bury (depending on the relation of lateral to vertical accretion) all human constructions given time. Such a pattern is evident in a living megacity like Singapore, where the modern shopping thoroughfare of Orchard Road follows the course of a river. Orchard Road sits within a river valley, but the flow of the river today is controlled by the Stamford Canal, which runs beneath and alongside Orchard Road, and which floods during intense tropical rainstorms (e.g. in 2011). The authorities in Singapore are currently able to improve the drainage systems and manage the flooding; but, were humans to disappear, it is likely that the river would eventually overrun its human constraints (Fig. 5). Fluvial systems can thus, once human forcing of them ceases, rapidly (from a geological perspective) revert to their original patterns. This contrasts with the behaviour of large-scale chemical cycles such as the carbon cycle and associated climate and ocean chemistry perturbations, which will take tens to hundreds of millennia to regain equilibrium once human pressure on them stops. There is an even greater contrast with anthropogenically perturbed global biota, which may ultimately retain its diversity (if human impact ceases), but with a radically different assemblage of animal and plant taxa, as was the case after each mass extinction event in Earth's history.

There is another scenario too, with geological analogy to the persistence of the influence of vegetation in rivers after the Permian-Triassic extinction: one in which humans, or if humans were to become extinct, their technological constructions (Haff, 2014), continue to evolve and develop the surface of planet Earth over geological timescales. In this scenario the change to rivers would represent a geologically long-lived state change and departure from the pre-human world. A fundamental character of this state (if it resembles the history of the Anthropocene to date) is one of continuing rapid evolution of form and process, given the inherent impetus of technological systems towards change. In this scenario, the change to river systems induced by humans would fully resemble the great events of the past, the mineralogical changes in fluvial systems induced by the oxygenation of Earth's atmosphere at 2.4 Ga, and the evolution of a terrestrial biosphere with vascular plants at 0.416 Ga. Earth's rivers have undergone a fundamental state change; whether it is a geologically long-lived one, only time will tell.

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Figures

Fig. 1. Time-line of major events in the evolution of river systems from the Precambrian to present: data for the development of the terrestrial plant biosphere is taken from Davies and Gibling (2010, 2013). Steps 1 to 3 on the Earth events timeline signify the three stages of evolution of rivers identified here. Dates on the vertical axes are in Ga (billions of years).

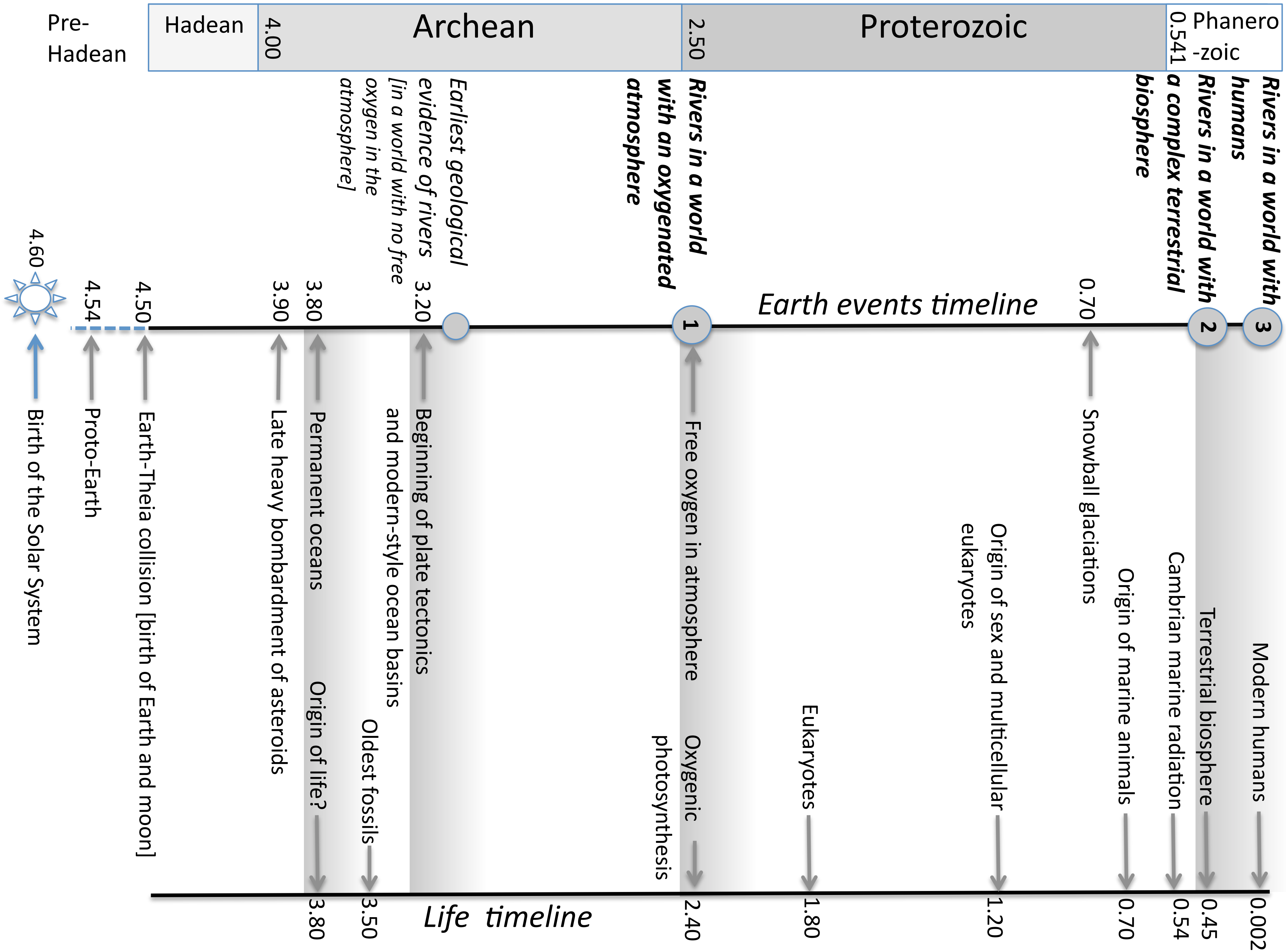
Fig. 2. Burrows of the trace fossil *Beaconites antarcticus*, thought to represent the activity of early terrestrial lungfish. This burrow is in sandstone interpreted to

represent meandering river systems of Devonian age at Freshwater West, South Wales (image David Siveter, University of Leicester).

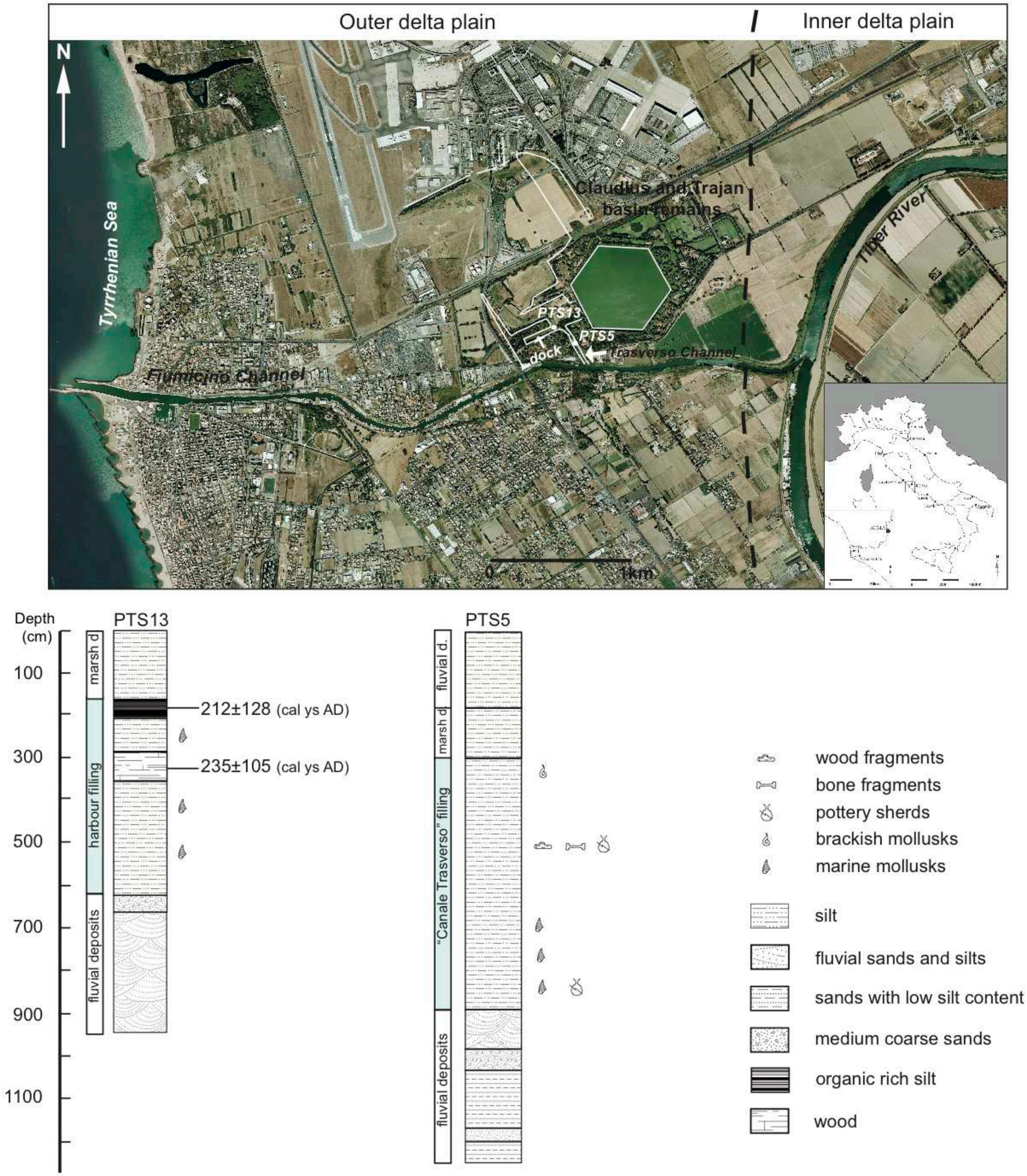
Fig. 3. The human excavated Fiumicino Channel, connecting the ancient harbour at Portus to the River Tiber: constructed at the time of the emperor Claudius during the first century AD. The sedimentary motifs preserved in cored sediments from PTS5 in the Traverso Channel and PTS13 in the dock show the anthropogenic signature clearly imposed through a change in sedimentary motif (above the dredging surface in PTS5, and the harbour foundation in PTS13), through mineral content, fauna and artefacts of wood, bone and pottery (see also Mazzini et al., 2011).

Fig. 4. The interior of the Thames Tunnel in the mid-19th century. Image from Wikimedia Commons available at http://en.wikipedia.org/wiki/File:Thamestunnel.jpg

Fig. 5. Rivers in a modern, technologically advanced megacity: beneath and alongside Singapore's premier shopping thoroughfare of Orchard Road runs the human constructed Stamford Canal, itself a conduit for a natural stream. During severe tropical storms parts of Orchard Road flood, and whilst human constructs can keep the river contained, were humans to disappear, the natural river system here would eventually restore (image Stephanie Kane, Indiana University).



Pre-Hadean
Hadean
4.00
Archean
2.50
Proterozoic
0.541
Phanerozoic
Earliest geological evidence of rivers [in a world with no free oxygen in the atmosphere]
Rivers in a world with an oxygenated atmosphere
Rivers in a world with a complex terrestrial biosphere
Rivers in a world with humans
Earth events timeline
4.60
4.54
4.50
3.90
3.80
3.20
0.70
1
2
3
Birth of the Solar System
Proto-Earth
Earth-Theia collision [birth of Earth and moon]
Late heavy bombardment of asteroids
Permanent oceans
Beginning of plate tectonics and modern-style ocean basins
Free oxygen in atmosphere
Snowball glaciations
Origin of life?
Oldest fossils
Oxygenic photosynthesis
Eukaryotes
Origin of sex and multicellular eukaryotes
Origin of marine animals
Cambrian marine radiation
Terrestrial biosphere
Modern humans
Life timeline
3.80
3.50
2.40
1.80
1.20
0.70
0.54
0.45
0.002



Outer delta plain
Inner delta plain
N
Tyrrhenian Sea
Claudius and Trajan basin remains
Tiber River
PTS13
PTS5
dock
Trasverso Channel
Fiumicino Channel
0
1km
Depth (cm)
100
300
500
700
900
1100
PTS13
marsh d
harbour filling
fluvial deposits
212±128 (cal ys AD)
235±105 (cal ys AD)
PTS5
fluvial d.
marsh d
"Canale Trasverso" filling
fluvial deposits
wood fragments
bone fragments
pottery sherds
brackish mollusks
marine mollusks
silt
fluvial sands and silts
sands with low silt content
medium coarse sands
organic rich silt
wood